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Photodisintegration of oxygen

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With 12 figures in the text

SUMMARY

The (γ,p) and (γ,α) reactions in O^{16} have been studied. Oxygen gas was irradiated in the bremsstrahlung beam of a 35 Mev synchrotron. The photoprotons were recorded by nuclear emulsions. Three different maximum bremsstrahlung energies were used: 20.5, 23, and 26 Mev. The low energy irradiation gives a proton spectrum containing well resolved peaks. They are attributed to transitions from resonances in O^{16} to the ground state of N^{15}. There is a very good agreement with the breaks found in the activation curve of the (γ,n) reaction. The information about the resonances in the low energy region is then used to analyze the proton spectrum at the medium energy. Finally, the proton spectrum at the highest irradiation energy is analyzed by means of the information from the other two irradiations. In this way it is possible to resolve the proton spectra in transitions from various resonances or groups of resonances in O^{16} to the ground state and the excited states of N^{15}. The angular distributions of the strongest proton groups have been studied. The information about the photodisintegration of O^{16} obtained in the present work is compared with the predictions of the various models proposed to explain the photodisintegration.

Below the threshold of the (γ,p) reaction the photodisintegration of O^{16} was studied by investigating the (γ,α) reaction. Nuclear emulsions were soaked in water in order to increase the oxygen content and then irradiated directly in the synchrotron beam. The α-tracks from the photodisintegration of oxygen were identified by the short, heavily ionized track of the recoiling daughter nucleus. The α-particle spectrum shows two groups corresponding to levels in O^{16} at 11.3 and 12.5 Mev. This result is compared with the theoretical calculations based on the α-particle model for O^{16}. The agreement with the theory is very good.

Introduction

The photodisintegration of oxygen has been studied rather extensively in recent years. Several different processes have been studied, (γ,α) [1–3], $(\gamma,4\alpha)$ [4–6], (γ,n) [7,8], and (γ,p) [9–11]. All these experiments indicate that the photons are absorbed in many narrow resonances. The α-particle spectra have an irregular shape. They are composed of many closely spaced groups corresponding to resonances in the oxygen nucleus. The spectra are so complicated, however, that it is very difficult to resolve them into single resonances. The resonances also present themselves as breaks in the photoneutron activation curve. It is possible to analyze the activation curve and find the position and strength of the resonances. The smallest resonances may escape detection, however, and it is also impossible to decide if there is any continuous component in the cross-section curve. The photo-proton spectra are also composed of many closely spaced groups. The number of levels is so high, especially in the region of the giant resonance, that the proton groups do not show up separately but merge into a more or less continuous distribution. In the tail below the giant resonance, however, the level density is lower. In this energy range fairly well separated proton groups have been found. There is a close correspondence between these groups and the breaks in the photoneutron activation curve [11].

In order to determine the mechanism of the photodisintegration it would be desirable to know in detail how the excited O^{16} nucleus decays to the various levels in the daughter nucleus N^{15}. The difficulty in analyzing the data is that there are so many resonances in O^{16}. The number of transitions is even greater, since several levels in the daughter nucleus are involved in the decay. The resulting photo-proton spectra, for example, will then be very complicated. One way to overcome this difficulty is to use a low bremsstrahlung energy, so that only a few levels close to the threshold are excited. This precedure, of course, gives no information about the giant resonance. On the other hand, a spectrum obtained with the maximum bremsstrahlung energy set above the giant resonance will be too complicated to analyze in detail. A possibility of solving this problem is to record several spectra with different maximum bremsstrahlung energies. The information about the levels obtained with the lowest energy can be used to analyze the spectrum of the next higher energy and so on.

A prerequisite for the use of this method is that the level density of both the excited nucleus and the residual nucleus is not too great. Otherwise very many different proton spectra are required and too much work is involved. This limits the method to light nuclei. Among them O^{16} seems to present the most favorable case. The level density of O^{16} is comparatively low since it is double-magic. The residual nucleus N^{15} has also a low level density and its first excited state is fairly high up, at 5.3 Mev. For this reason not so many proton spectra are needed. In the present work we have used the following maximum bremsstrahlung energies: 20.5, 23, and 26 Mev. The first spectrum gives the levels in the tail below the giant resonance, the second one gives the lower part of the giant resonance and the third one the upper part of the giant resonance.

The (γ,p) reaction gives information about the photodisintegration above about 14 Mev. Below this energy additional information can be obtained from a study of the (γ,α) reaction. The transitions to the ground state of C^{12} are expected to be predominant in this energy range compared with transitions to the excited states. The α-particle spectra then directly give the resonances in O^{16}. It would be very interesting to extend the study of the (γ,α) reaction to higher energies. It is then necessary, however, to use the same method as has been employed for the (γ,p) reaction, i.e. recording spectra for several different bremsstrahlung energies. The technique used for the measurement of the α-spectra is very tedious, however. Hence it would require a very great effort to make a complete investigation of the (γ,α) reaction. We have, therefore, limited ourselves in the present work to lower energies.

Very useful information about the nature of the resonances and the mechanism of the photodisintegration can be obtained from the angular distribution of the emitted particles. It is necessary, however, to be rather cautious in the interpretation of the experimental results. The angular distribution for particles in a certain energy range might contain contributions from transitions of different types. Let us assume, for example, that we are investigating transitions from a number of levels in O^{16} to a certain level in N^{15}. We can further assume that some of the O^{16} levels have the spin

1+ and some the spin 2+. It is quite evident that the angular distribution for all the particles taken together does not tell anything about the O^{16} levels. It is necessary to plot the angular distribution for each transition separately. This is clearly impossible since most of the corresponding proton groups are not separated from each other. In certain cases, like the present one, some strong peaks rise well above the rest and it is possible to find the angular distribution for each peak.

In some cases it is known that all the levels in a certain range have the same spin. In the giant resonance, for example, the greater part of the levels have the spin 1−. This fact makes possible a meaningful intrepretation of angular distributions, even if the single transitions are not resolved.

The aim of the present work has been to resolve the proton spectra in groups corresponding to transitions between levels in O^{16} and N^{15}. In the low energy region peaks were found corresponding to transitions from resonances in O^{16} to the ground state of N^{15}. In the giant resonance region it was not possible to find any single resonances, but the branching to the various excited states in N^{15} was studied. The proton spectra were used for a calculation of the cross-section curve for the (γ,p) reaction. The angular distributions were studied for the strongest proton groups.

The study of the (γ,α) reaction was limited to the low energy range, where only ground state transitions occur. The energy distribution and the angular distribution were studied.

Experimental arrangement

(γ,p) *reaction*

In these experiments oxygen gas at a pressure of 1–2 atm. was irradiated by the bremsstrahlung beam from the 35 Mev synchrotron at the University of Lund. The beam was collimated with lead to give a pencil with a diameter of 2 cm at the position of the oxygen target. The beam was passed through the nuclear emulsion camera containing the oxygen gas. The emulsions used to detect the protons were mounted in the camera parallel to the X-ray beam. The near edge of the emulsions was 2 cm from the centre of the beam. Ilford C2 emulsions, 200 μ thick, were used in the greater part of the present work. In some cases 400 μ emulsions were used to prevent the high energy protons from passing all the way through the emulsion.

The dose received by the target was monitored by a transmission chamber calibrated against a Victoreen thimble at the centre of a 6 cm cube of lucite. Three different maximum bremsstrahlung energies were used: 20.5, 23, and 26 Mev.

After processing, the plates were scanned with Leitz microscopes using an 8× ocular and 22× and 100× objectives. The length of the tracks was determined by measuring the projected length of the tracks on the plane of the emulsion and the final depth of the tracks. After determination of the shrinkage factor, the length of the tracks could be calculated, Only those tracks were accepted which had a direction compatible with an origin in the irradiated part of the gas.

Not all the tracks in the emulsions can be attributed to the (γ,p) reaction in oxygen. A great number of neutrons are produced in this experiment, especially in the lead collimator. The neutrons give recoil protons in the emulsions and some of them go out through the emulsions in such a direction that they seem to come from the target, since the direction of motion cannot be determined with certainty. This background can be corrected for in the following way: The plates are scanned also for tracks coming into the emulsions from the wrong direction. The selection rules considerable fading could occur if the temperature were not kept sufficiently low. For this purpose cold water was dropped onto the plates during the irradiation.

The plates were mounted 2 meters from the target of the synchrotron. The bremsstrahlung beam was filtered through 80 cm of lucite. This cuts down the low energy end of the spectrum, thereby reducing the blackening of the plates. A stronger irradiation can, therefore, be used. The dose was measured with a transmission ionization chamber calibrated against a standard Victoreen chamber, placed in the plate irradiation position. The plates were irradiated with 100 roentgens. The maximum bremsstrahlung energy was 19 Mev.

In this experiment Ilford E1 emulsions were used. They were developed according to Van der Grinten's grain-gradation process, in order to minimize fogging. After development the plates were processed in the usual way.

An area of 14 cm^2 was scanned for oxygen α-tracks. Ninety-four tracks having the typical short recoil stub were found. In a final inspection only 53 of these were accepted. The rest were rejected as doubtful cases. The most common reason for rejecting a track was that the law of momentum balance was not fulfilled. After this procedure the length of the accepted tracks was accurately determined by measuring the projected length on the plane of the emulsion and the dip of the tracks.

For the calculation of the length of the tracks it is necessary to know the shrinkage factor. Since the emulsions swell from the absorption of water, the shrinkage factor is greater than for dry emulsions. It is, therefore, necessary to know it with a fairly high degree of accuracy. It was determined in a separate experiment in which a plate was soaked in water containing a very small amount of polonium. This plate was processed in exactly the same way as the other plates. A number of polonium α-tracks in various directions were measured. From this a value of the shrinkage factor was obtained. It turned out to be independent of the dip of the tracks.

The usual range-energy relation for E 1 emulsions cannot, of course, be used for these water-soaked plates. A new range–energy curve was obtained in the following way: The above-mentioned measurements on the plate containing polonium α-tracks determine one point on the curve. Starting from this point the curve is calculated from the theoretical formula. This method should be accurate enough, especially since the present work is concerned mainly with energies not too far from the energy of the polonium α-particles.

Results

(γ,p) *reaction*

Figures 1–3 show the photo-proton spectra for the maximum bremsstrahlung energies 20.5, 23, and 26 Mev, respectively. All three spectra exhibit a pronounced fine structure. This structure is partly due to resonances in the photon absorption and partly to the branching of the proton emission to various excited levels in the daughter nucleus N^{15}. In order to interpret these spectra it is necessary to start with the one obtained at the lowest bombarding energy.

For the 20.5 Mev irradiation the interpretation is straight-forward. Practically only the ground state of N^{15} can be reached by the protons. Hence each peak in the proton spectrum corresponds to a resonance in the photon absorption. In Fig. 4 part of the spectrum is shown more in detail with some more tracks included, and a comparison is made with the breaks found in the (γ,n) activation curve [7, 8]. The arrows in the figure indicate the position of the breaks. In some cases where two

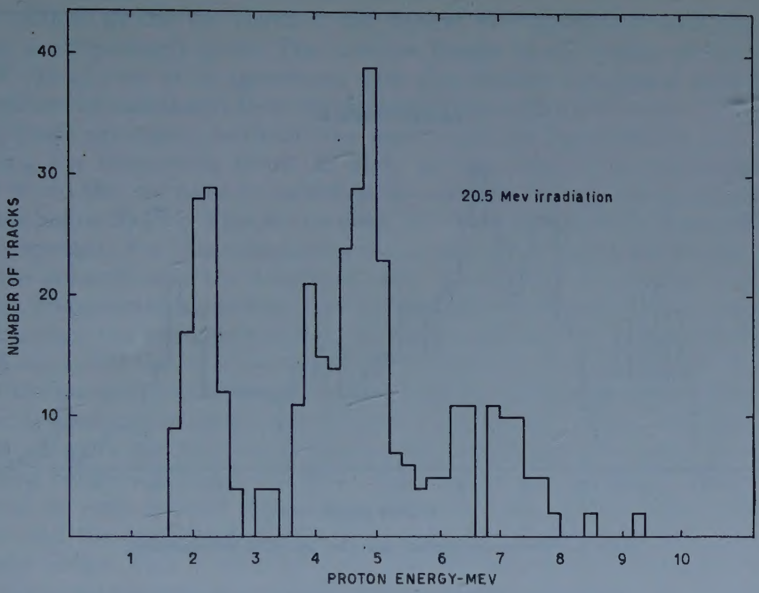


Fig. 1. Proton spectrum for the 20.5 Mev irradiation.

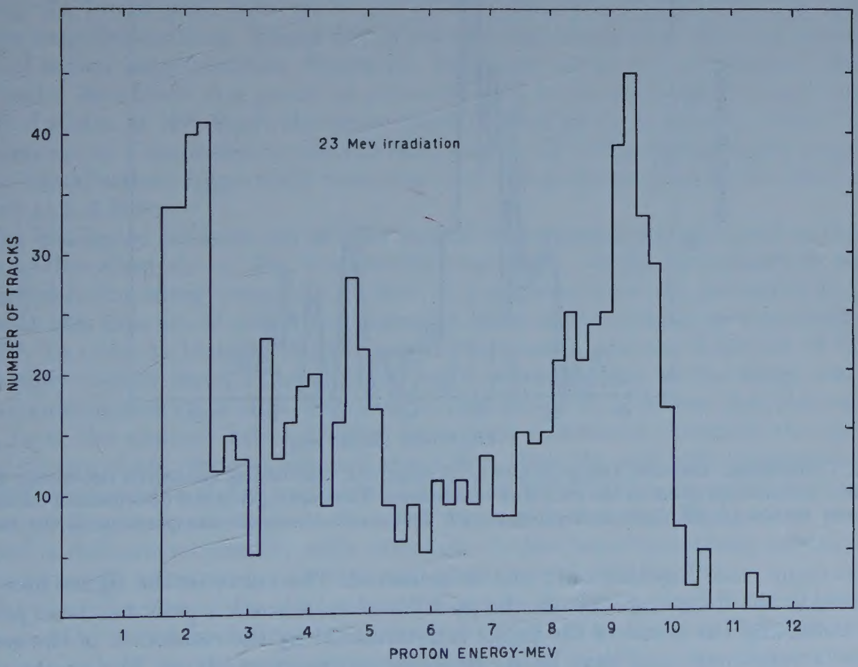


Fig. 2. Proton spectrum for the 23 Mev irradiation.

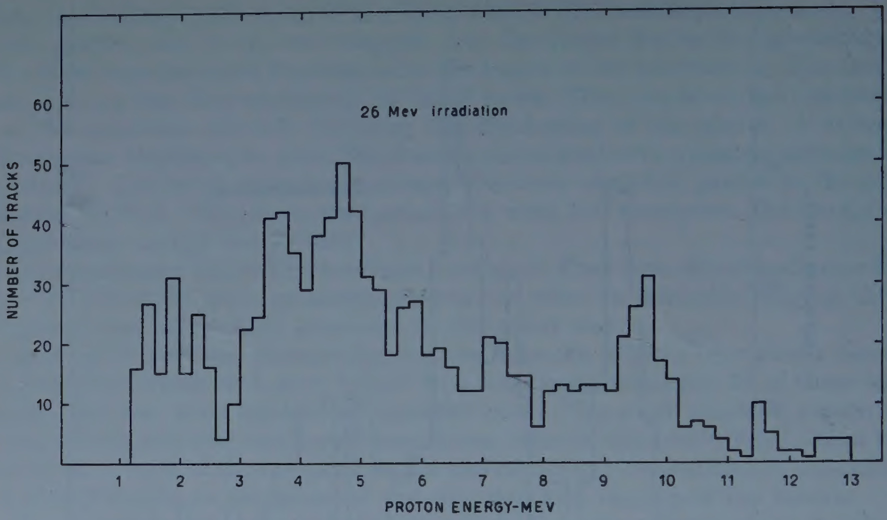


Fig. 3. Proton spectrum for the 26 Mev irradiation.

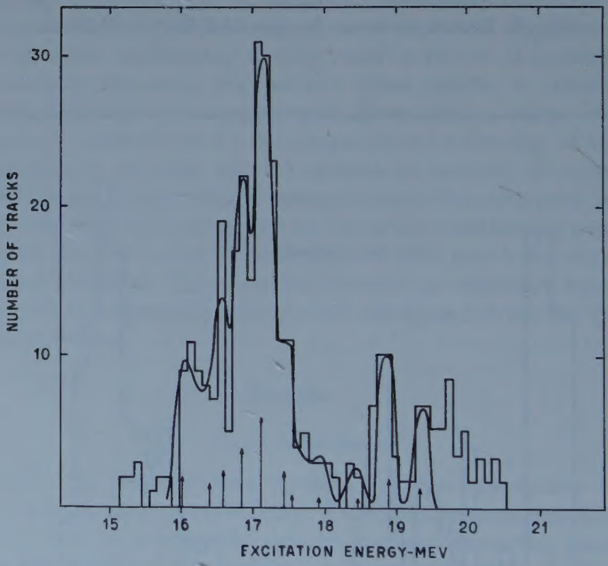


Fig. 4. Comparison between the (γ,p) and (γ,n) reactions. The histogram shows the energy distribution of the photoprotons in the 20.5 Mev irradiation. The curve gives the distribution calculated from the breaks in the (γ,n) activation curve. The arrows indicate the position of the breaks.

breaks come close together only one is indicated. The curve in the figure has been obtained in the following way: At the position of each break a peak has been placed. The width and the shape of the peaks is determined by the resolution of the experimental arrangement and have been calculated as discussed above. The height of the peaks has been chosen in order to fit the histogram as well as possible. The peaks are then added, giving the curve in the figure. The agreement with the measured spectrum is surprisingly good. The relative height of the peaks (indicated by the length of the arrows) is in agreement with the relative integrated cross-section for the resonances as calculated from the breaks in the activation curve. This fact shows that the good agreement between the curve and the histogram is not accidental.

Knowing the resonances below 20 Mev, we can resolve the spectrum in Fig. 2. In order to do this we have to calculate the contribution in this spectrum from the resonances below 20 Mev. This can be done, provided we know the shape of the bremsstrahlung spectra. For this calculation we have used a Schiff distribution [15] modified for the absorption in the doughnut wall. The 20.5 Mev spectrum is transformed to 23 Mev bremsstrahlung energy and subtracted from the 23 Mev spectrum. Before the subtraction the two spectra have to be normalized to correspond to the same dose of X-rays. For this it is essential that the dose has been measured very carefully and that the geometry and the scanning have been exactly the same in the two runs. These conditions are not quite well fulfilled. A better way to carry out the normalization is to compare the number of tracks in a certain energy range. Let us consider the protons between 6.2 and 7.8 Mev. These limits are chosen so that the protons correspond to only ground state transitions in both spectra. Hence the 23 Mev spectrum and the transformed 20.5 Mev spectrum should have the same shape in this energy range. This is actually true. The two spectra are, therefore, normalized to have the same number of protons between 6.2 and 7.8 Mev. After the subtraction the spectrum of Fig. 5 is obtained.

The protons of this spectrum correspond to the absorption of photons in the energy range 20.5–23 Mev. Most of the protons ($\sim 70\%$) correspond to ground state transitions giving the broad peak between 8 and 10 Mev. Between 4 and 8 Mev the spectrum shows large fluctuations. This is due to the fact that this part is obtained by subtraction of rather large numbers. Hence the statistical errors are considerable. Between 1.5 and 4 Mev there is a group of protons which must correspond to transitions to excited states in N^{15}. Since the upper limit for this group is around 4 Mev, it must correspond to a transition to the 6.3 Mev state in N^{15}. The higher states may make some contribution. Apparently there are very few protons going to the first excited states at 5.3 Mev.

The difference between the 26 Mev and 23 Mev spectra was obtained in the same way as described above. Fig. 6 shows this spectrum, which corresponds to photons absorbed in the energy range 23–26 Mev. It is apparent that the ground state transitions in this case are of rather low intensity. Most of the protons go to excited states in N^{15}. In order to identify the various proton groups, one can make use of the fact that they should have a sharp lower limit, corresponding to the sharp cut-off in photon absorption at 23 Mev. The cause of this cut-off is, of course, that the contribution from the photons below 23 Mev have been subtracted. Actually the spectrum exhibits two sharp edges at about 3 and 4 Mev. They fit well with transitions to the 6.3 Mev state and to the two states at 7.3 Mev in N^{15}. There is no evidence of a group corresponding to transitions to the first two excited states. The proton group at 2 Mev is difficult to identify with certainty. It has been tentatively assumed that it corresponds to transitions to the two levels at 9.1 Mev in N^{15}.

The identification of the various proton groups makes it possible to calculate the cross-section curve for the (γ,p) reaction in oxygen. It is shown in Fig. 7 to the left. Absolute values for the cross-section can be calculated from the X-ray dose, the geometry of the experimental set-up, and the number of tracks. The present work

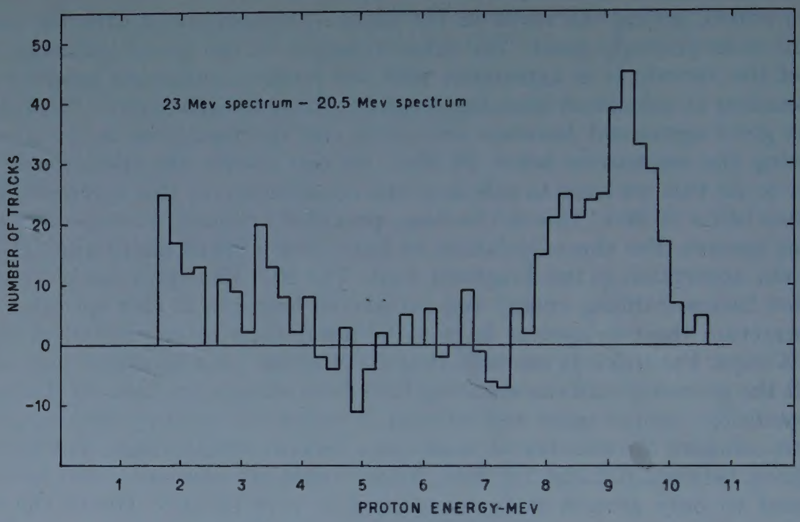


Fig. 5. Proton spectrum corresponding to photon absorption in the energy range 20.5–23 Mev.

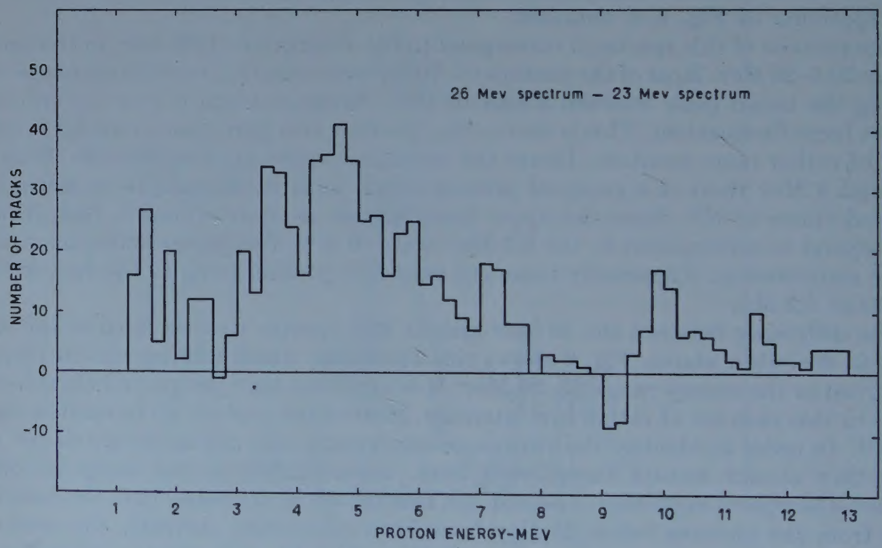


Fig. 6. Proton spectrum corresponding to photon absorption in the energy range 23–26 Mev.

is not so well suited for such a calculation, however. We have, therefore, used the cross-section curve for ground state transitions from the work of Stephens *et al.* [9]. It enables us to calculate an absolute scale on the cross-section curve. The integrated cross-section from threshold to 25.5 Mev turns out to be 76 Mev-mb. There seem to be no other works giving a value for the cross-section except a recent work by Svantesson [16] on the $(\gamma,p\gamma')$ and $(\gamma,n\gamma')$ reactions in oxygen. He obtains for the integrated

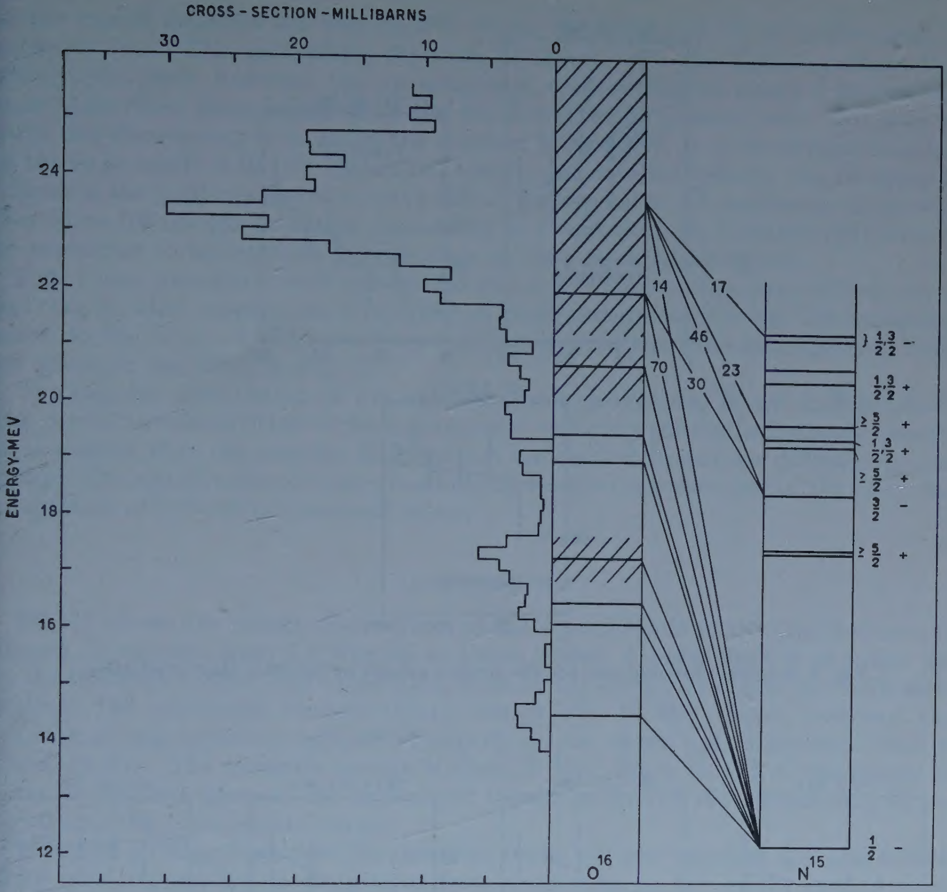


Fig. 7. Level scheme for the photodisintegration of O^{16}. The cross-section curve is plotted to the left. The numbers inserted for some of the transitions denote the relative branching ratios in per cent.

cross-section from 20 Mev to 25 Mev a value of 68 Mev-mb. The present work gives the value 58 Mev-mb, in satisfactory agreement.

It is interesting to compare the cross-section curves for the (γ,p) and (γ,n) reactions. The general shape and the position of the giant resonance seem to be the same. The (γ,n) measurements [17–19] do not agree quite well with each other, but the peak falls in the mean at around 23 Mev. For the low energy part the peaks of the (γ,p) curve have already been compared with the breaks in the (γ,n) activation curve (Fig. 4). If we do the same for higher energies we obtain good agreement with the work of Katz *et al.* [7]. They found in the lower part of the giant resonance two breaks at 20.7 and 21.9 Mev. The (γ,p) curve shows two peaks exactly at these values. A comparison with the work of Penfold and Spicer [8] is more difficult, since their data are not quite complete in this energy range.

In the low energy range there is a peak at about 14.5 Mev. Part of the protons assigned to this level might be due to transitions from resonances at about 20 Mev

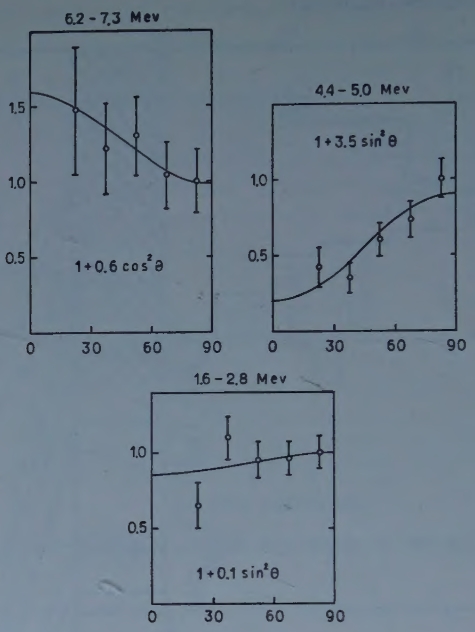
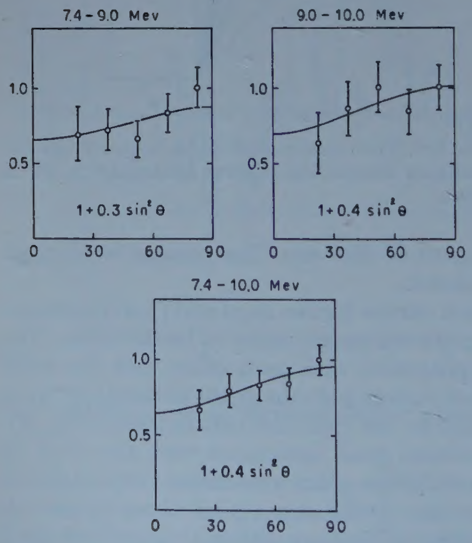


Fig. 8. Angular distributions for the proton groups in the 20.5 Mev irradiation.



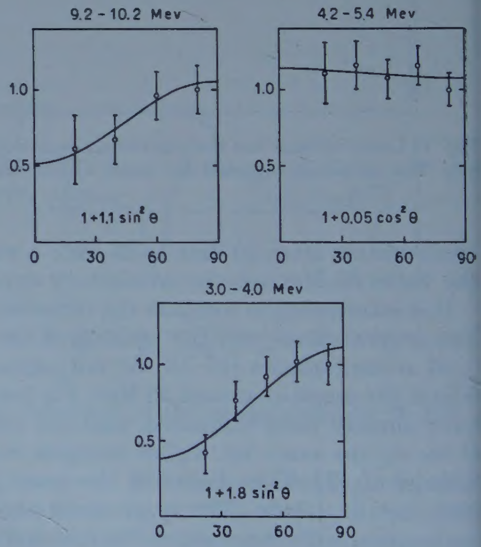


Fig. 9. Angular distribution for the proton groups in the 23 Mev irradiation.

Fig. 10. Angular distribution for the proton groups in the 26 Mev irradiation.

to the exited states at 5.3 Mev in N^{15}. Hence the height of the 14.5 Mev peak is an upper limit. This contradicts the work of Spicer, who also finds a peak at this energy, His peak, however, has an integrated cross-section of about 6 Mev-mb or more than three times bigger than the one found in the present work. One way to solve this discrepancy is to study the reaction $N^{15}(p,\gamma)O^{16}$. It is the inverse reaction to the (γ,p) reaction in O^{16}. Hence the theorem of detailed balance can be applied. A peak in the (γ,p) cross-section curve should correspond to a resonance in the excitation curve for the (p,γ) reaction. According to recent work by Lidofsky [20] there is no resonance to match such a large peak as that reported by Spicer.

Fig. 7 also contains a level scheme for the (γ,p) reaction. The cross-section curve has been divided, more or less arbitrarily, in levels and groups of levels. The branching ratios to the levels of N^{15} have been calculated from the preceding spectra. They are given in per cent in Fig. 7.

The angular distribution of the various proton groups are shown in Figs. 8–10. The curves have been fitted to the experimental values by the method of least squares. It is evident that the angular distributions are quite different for different proton groups. The significance of these distributions for the interpretation of the photodisintegration of O^{16} will be discussed below.

(γ,α) *reaction*

Fig. 11 shows the energy distribution of the α-particles from the (γ,α) reaction in oxygen. It extends from 2.5 Mev up to about 8 Mev. A lower limit is of course set by the Coulomb barrier. The upper limit is set by the energy available for the disintegration. The maximum bremsstrahlung energy was 19 Mev. Since, however, the bremsstrahlung spectrum falls off so rapidly at the upper end, a practical limit is about 18 Mev. The available energy is then 11 Mev. Since only $\frac{3}{4}$ of the energy is taken up by the α-particle, the upper limit should be about 8 Mev, which is in agreement with the experimental value.

The most striking feature of the spectrum is the two strong peaks at 3 and 4 Mev. They must correspond to transitions from resonances in O^{16} to the ground state or the first excited state in C^{12}. Transitions to higher excited states are energetically impossible. If one or both of the groups were due to transitions to the first excited state, one would expect such a group to be accompanied by a ground state transition with 3.3 Mev higher energy. There is no trace of such groups. Theoretically the ground state transitions in this energy range are expected to be stronger than transitions to the first excited state. Experimentally it is found that even at 17 Mev the ground state transition is considerably stronger. Hence we conclude that the α-groups at 3 and 4 Mev are ground state transitions. The energy values for the two corresponding levels in O^{16} are 11.3 Mev and 12.5 Mev.

The width of the peaks in Fig. 11*a* is due to the fairly great uncertainty in the energy measurements. This is partly caused by the difficulty of measuring the length of the tracks quite accurately. The origin of the α-tracks is not so well defined. The swelling of the emulsion by the uptake of water may not be quite uniform, which introduces an additional error.

The selection of track having a recoil stub is of course not absolutely perfect. Even if we rejected every track which did not meet all the requirements for an event of this kind, there still is some chance that the distribution also contains some α-tracks from the disintegration of bromine and silver. It is, therefore, of interest to

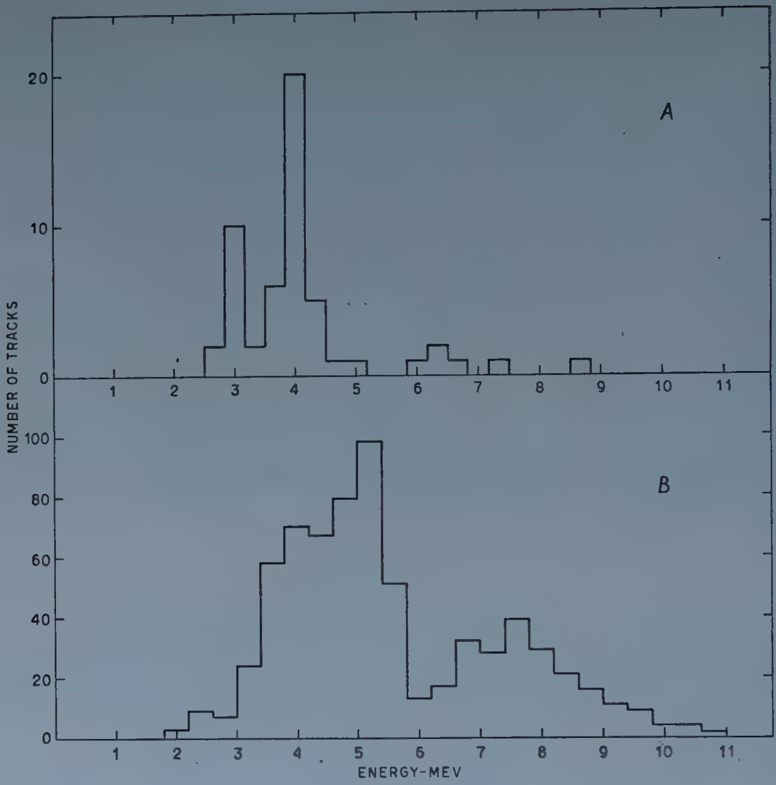


Fig. 11. Energy distribution for the α-particles from the (γ,α) reaction in (*a*) O^{16}, (*b*) bromine and silver.

investigate how this can affect the energy distribution. We therefore measured a number of single α-tracks. A histogram of these tracks is shown in Fig. 11b. It has a characteristic shape with two peaks at about 4.5 Mev and 7.5 Mev. Distributions of this type have been observed before [2, 21]. The low energy peak has been attributed to "threshold-favoured" α-emission. This means that the excited nucleus first emits a neutron or proton which leaves the residual nucleus with an excitation energy higher than the binding energy of an α-particle but below the binding energy of a neutron or proton. Thus the α-particle emission has only to compete with γ-emission, and it is reasonable to expect a low energy peak in the α-spectra.

If some mistake has been made in the selection of α-tracks, one would expect the histogram in Fig. 11*a* to contain some α-particles from bromine and silver, having the energy distribution shown in Fig. 11*b*. A comparison of the two spectra in Fig. 11*a* and 11*b* shows that they are of a very different shape. Hence it seems safe to assume that the selection of "oxygen" tracks is reasonably good.

The angular distribution of the α-tracks from oxygen is plotted in Fig. 12. Theoretically the distribution should be symmetrical around 90°, and experimentally it is found that the number of tracks in the forward and backward directions are the

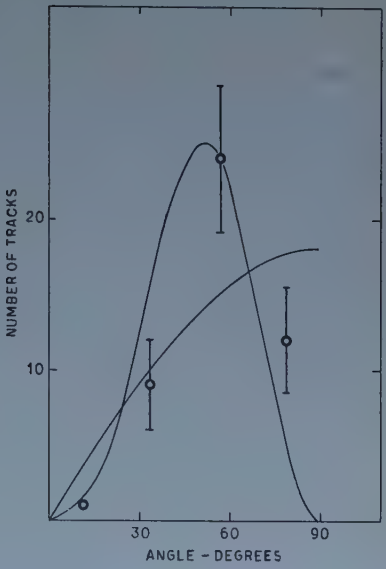


Fig. 12. Angular distribution of the α-particles from the (γ,α) reaction in O^{16}. The two curves correspond to (*a*) isotropic distribution, (*b*) a distribution of the form $\sin^2 2\theta$.

same within the limits of the statistical errors. The distributions in the forward and backward directions have, therefore, been added in order to improve the statistics. The two curves in the figure correspond to isotropic distribution and a distribution of the form $\sin^2 2\theta$. The latter one is expected theoretically [22, 23]. The α-tracks from bromine and silver have an isotropic distribution. It is evident that the experimental points do not fit either of the two curves very well. The $\sin^2 2\theta$ distribution fits slightly better, but a good fit is only obtained if one can explain the excess of tracks at right angles to the beam. There is indeed a natural explanation for such an excess. A few of the α-tracks from bromine and silver might have been identified by mistake as oxygen α-tracks. An error of this kind is most likely to occur for tracks which have a large dip in the emulsion. Most of these tracks fall for pure gemetrical reasons in the interval around 90°. Hence this effect will produce an excess of tracks at right angles to the beam. It will be noted that 5–6 extra tracks in the interval 60–90° can bring the $\sin^2 2\theta$ distribution into good agreement with the experimental points. This seems to be a satisfactory interpretation of the angular distribution.

It is interesting to compare the present work with some earlier work by Millar and Cameron [2], and Stoll [3]. They used higher bremsstrahlung energies and the α-spectra are, therefore, a complex mixture of transitions to various levels in the residual nucleus. In the low energy region there is a broad peak at about 13 Mev, which might partly correspond to the two levels found in the present work. Above 14 Mev the cross-section decreases and remains low until it rises to a rather strong peak at about 17 Mev. The decrease of the cross-section above 14 Mev might be explained by the onset of proton emission, which will compete very strongly with with the α-emission. This might also explain why there are so few α-particles above 5 Mev in the present experiment.

Discussion

(γ,p) *reaction*

The present determination of the cross-section for the (γ,p) reaction and previous work on the (γ,n) reaction render it possible to make a detailed comparison between these two reactions. It has already been noted that there is a farily good agreement between the relative height of the proton peaks and the integrated cross-sections calculated from the breaks in the activation curve for the (γ,n) reaction. It is difficult, however, to make a comparison for single resonances, since there is some lack of agreement between the works of Katz *et al.* and Penfold and Spicer. The reported cross-sections for single resonances differ with factors up to five, even for the strong resonances. It is safer to make a comparison between the (γ,p) and (γ,n) cross-sections in certain energy intervals, taking the sum of several levels. The experimental errors will then be less important. A comparison of this kind is shown in Table 1. The first energy range considered is around 17 Mev, and it comprises the strong resonances in this region. The (γ,n) cross-section has been taken as the mean of the values reported by Katz *et al.* and by Penfold and Spicer. The second case considered is the strong resonance at 18.9 Mev. The (γ,n) value has been taken from Katz *et al.* The data of Penfold and Spicer are reported to be not quite complete in this region. Furthermore, the cross-sections are compared in the range 20.5–21.5 Mev. The (γ,n) value is taken from the work of Penfold and Spicer, which is the most detailed one in this energy range.

The resonances considered so far are located below the giant resonance. It would be of great interest to make a comparison also for the giant resonance. There one encounters the difficulty that several states in the residual nuclei can be reached by the emitted nucleons. The branching ratios are not well known. An approximate comparison can be made, however. We limit ourselves to the energy range 23–24 Mev, i.e., the peak of the giant resonance. The neutrons can only reach the ground state and the first two excited states. Hence we have to limit the comparison to these states. The experimental value for the (γ,p) reaction is, therefore, taken as the integrated cross-section times the sum of the branching ratios to the ground state and the 6.3 Mev state. As an experimental value for the (γ,n) reaction the mean of the reported values has been used [17, 19].

The great interest of a comparison between the (γ,p) and (γ,n) cross-sections comes from the fact that it gives information about the charge independence of the nuclear forces. This problem has been discussed by Gell-Mann and Telegdi [24]. They show that if the nuclear forces are charge independent the (γ,p) and (γ,n) cross-sections must, for each individual state, be identical with each other as function of energy and angle, except to the extent that interference occurs. A correction has to be applied for the penetration of the barrier. The barrier penetration factors for protons were obtained from Feshbach, Shapiro and Weisskopf [25] and for neutrons from Blatt and Weisskopf [26]. They, of course, depend on the angular momentum, l, of the emitted particle. The ratio between proton and neutron emission has been calculated for $l = 0, 1, 2$, assuming charge independence. In the case of the last line in Table 1 some assumption has to be made about the branching ratios for the neutrons to the levels in O^{15}. It is assumed that the ratio of the reduced widths are the same for the neutrons as for the protons. It should be remarked, however, that the results are rather insensitive to the branching ratios of the neutrons except for $l = 2$.

Table 1. Comparison between the cross-sections for the (γ,n) and (γ,p) reactions in O^{16}.

Energy range, Mev	Integrated cross-section Mev-mb		Ratio between the (γ,p) and (γ,n) integrated cross-sections			
	γ,p	γ,n	Experimental	Theoretical		
				$l=0$	$l=1$	$l=2$
16.5–17.5	3.5	1.6	2.2	1.1	1.9	10
18.9	1.1	0.66	1.6	1.0	1.2	2.5
20.5–21.5	3.3	3.4	1.0	1.0	1.0	1.5
23.0–24.0	13	10	1.3	1.1	1.4	3.2

Table 1 shows very well that there is good agreement between the experimental and calculated values for the ratio between the (γ,p) and (γ,n) cross-sections. The extent of the agreement depends on the value of l. Some other experimental evidence, which will be discussed later on, indicates that $l=1$ for the first two lines and $l=0$ for the last two. It is interesting to note that these values also give the best agreement in Table 1. The errors of the experimental values used in this comparison are so great, however, that it is dangerous to put too much emphasis on this point. The result of this comparison shows, at any rate, that the hypothesis of charge independence is fulfilled within the limits of the experimental errors.

The aim of the present work has been to obtain as much information as possible about the (γ,p) reaction in O^{16} in order to discriminate between the various models proposed to explain the photonuclear effect. The excitation can be collective and then leads to the formation of an ordinary compound nucleus. Another possibility is that the photoemission is a direct effect not involving a compound nucleus. The predictions of these two models are in general different. In the present discussion the experimental results will be compared with the ordinary compound nucleus model and also with the independent particle model of Wilkinson [27]. This latter model is based on the assumption that both the initial and final states can be described as shell model states.

Starting with the 17 Mev group of levels it will be noted that the protons have an angular distribution of the form $1+3.5\sin^2\theta$. For comparison a number of angular distributions have been calculated for different spin and parity values of the intitial and final states, assuming the formation of a well defined intermediate state. The calculation is made with the use of LS coupling, which should be the best approximation for these light nuclei. The calculated distributions are listed in Table 2. The table shows that the angular distribution for the 17 Mev group corresponds to $E1$ or $M1$ absorption, $E2$ is excluded. If the absorption is $E1$ then the difficulty arises of explaining why the $\sin^2\theta$ component, which corresponds to d-wave emission, is so predominant. On the basis of the compound nucleus model it is expected to be much less. Another difficulty arises if a comparison is made with the results in Table 1. If d-wave emission is the main mode of decay, then the calculated value for the ratio of the (γ,p) and (γ,n) cross-sections is much higher than the experimental value, implying that the hypothesis of charge independence is not fulfilled. If the absorption for the 17 Mev resonance is $M1$, the emission goes by p-wave and no difficulty of this

Table 2. Angular distributions for proton transitions between states in the excited O^{16} nucleus (spin J_C) to states in the residual N^{15} nucleus (spin J_N). S denotes the channel spin and l the orbital angular momentum of the proton.

J_C	J_N	S	l	Angular distribution
1−	1/2−	1	0	constant
1−	1/2−	1	2	$1+3/2\sin^2\theta$
1−	3/2−	1	0	constant
1−	3/2−	1	2	$1+3/2\sin^2\theta$
1−	3/2−	2	2	$1+\cos^2\theta$
1−	1/2+	0	1	$\sin^2\theta$
1−	1/2+	1	1	$1+\cos^2\theta$
1−	3/2+	1	1	$1+\cos^2\theta$
1−	3/2+	2	1	$6+\sin^2\theta$
1+	1/2−	0	1	$\sin^2\theta$
1+	1/2−	1	1	$1+\cos^2\theta$
2+	1/2−	1	1	$1+\cos^2\theta$
2+	1/2−	1	3	$1+6\cos^2\theta-5\cos^4\theta$

sort occurs. In order to explain the angular distribution, however, the assumption must be made that the channel spin 0 is predominant.

Wilkinson's theory predicts *d*-wave emission and an angular distribution of the form $1+1.5\sin^2\theta$. This is of the same general shape as the experimental one. However, there is still the difficulty of reconciling *d*-wave emission with the results of Table 1.

The protons from the resonances at 19 Mev have an angular distribution of the form $1+0.6\cos^2\theta$. This evidently excludes $E1$ absorption. A reasonably good fit is obtained for $E2$. $M1$ can also be made to fit if the contributions from the two channel spins are adjusted. The width of the 18.9 resonance is 53 ev. It is somewhat faster than the average if it is a $M1$ transition and normal if it is an $E2$ transition. Hence the choice between $M1$ and $E2$ cannot be made with certainty.

In the region of the giant resonance the absorption is assumed to have $E1$ character. It is not possible to resolve separate resonances, but the proton spectra are composed of groups corresponding to transitions to various levels in N^{15}. The branching ratios and the angular distributions for these transitions have been studied in the present work.

It is useful, before discussing these things, to give a brief summary of the information available about the levels in N^{15}. Besides the investigations discussed in the review article by Ajzenberg and Lauritsen [29], there is a work by Bent *et al.* [30] on the gamma-radiation from the deuteron bombardment of nitrogen and an investigation by Green and Middleton [31] on the proton groups in the same reaction.

It is very probable that the ground state with the spin 1/2− corresponds to a hole in the $p_{1/2}$ shell. The state corresponding to a hole in the $p_{3/2}$ shell is very likely the 6.3 Mev state, which is known to have odd parity and the spin 1/2 or 3/2. Very little can be said about the two states at 5.3 Mev. The stripping patterns indicate that the two levels have even parity. The gamma-ray measurements suggest the conclusion that the spin is equal or greater than 5/2. The levels at 7.17, 7.31, 7.58, and 8.82 Mev all have even parity. The first and third are formed in the stripping reaction by addition of a *d* neutron to the N^{14} core and the second and fourth by addition of an *s* neutron. The second and fourth levels have ground state transitions which the others do not have. Hence the levels at 7.31 and 8.82 Mev presumably have low spin values (1/2 or 3/2), while the levels at 7.17 and 7.58 Mev have higher values ($\geq 5/2$). Very little is known about the level at 8.57 Mev. Its spin is probably rather high since it has no ground state transition. The two levels at 9.06 and 9.16 Mev have odd parity and a rather low spin.

It is not possible to predict accurately, on the assumption of a compound nucleus, the branching ratios for the proton groups. The reduced width might fluctuate considerably. The penetration factors depend on l, and the spin and parity of the N^{15} levels will, therefore, in this way affect the transition probabilities. One therefore expects transitions to levels with low spin value and odd parity to be somewhat enhanced. This should be especially true for low energy protons. A comparison with the experimental results (Fig. 7) shows that the general trend goes in the expected direction.

Wilkinson's theory provides a definite prediction in this case. There are only two "parent states" in N^{15}, namely, the ground state and the 6.3 Mev state. If the excited nucleons are emitted directly, only these two states will be reached in the reaction. The transitions to these states are indeed predominant (about 60%). The remaining transitions, on the other hand, correspond to the case that the excitation energy is divided between two or several nucleons.

The angular distributions (Fig. 10) give further information about the proton emission. The ground state transitions have a distribution of the form $1 + 1.1 \sin^2 \theta$. Unfortunately the statistical errors are so great that not very much can be said about this distribution. On the compound nucleus picture a distribution of this form can be interpreted as a mixture of *s*-wave and *d*-wave emission. The experimental distribution can also be brought into agreement with the $1 + 1.5 \sin^2 \theta$ distribution predicted by Wilkinson's theory.

The angular distribution for the proton group going to the 6.3 Mev level is practically isotropic. This is expected on the basis of compound nucleus formation. The amount of *d*-wave emission will be rather small, due to the low penetrability of these low energy protons. The experimental distribution cannot be reconciled with the $1 + 1.5 \sin^2 \theta$ distribution required by Wilkinson's theory. This would seem to imply that the greater part of the emission to the 6.3 Mev state goes via compound nucleus formation.

The angular distribution for the protons going to the 7 Mev levels have a distribution of the form $1 + 1.8 \sin {}^2\theta$. Since these levels have even parity the emission can only go by *p*-wave. The experimental distribution is not inconsistent with this interpretation.

The conclusion of the present discussion is that the experimental results can be explained rather satisfactorily with the assumption of a compound nucleus. A lower limit for compound nucleus formation is about 80 per cent. It is, of course, still possible to assume that the independent particle model is valid, although most of the excited nucleons do not escape but collide with other nucleons forming a compound nucleus. The question then arises if it is possible to have this rather high probability for compound nucleus formation in a light nucleus like O^{16}. Theoretical calculations on the mean free path in nuclear matter have been performed by Goldberger [32] and by Lane and Wandel [33]. They obtain similar results which also are in agreement with scattering experiments. For the present energies a mean free path of about 8×10^{-13} cm is obtained. This corresponds to a probability of about 30 per cent for compound nucleus formation. These figures are, of course, very crude, but they indicate that it is difficult to explain the present results in this way.

It is evident from this discussion that it is difficult to explain the experimental results on the basis of a pure single particle theory. It seems to be necessary to take collective effects into account. One way to do this for nuclei near to closed shells is to describe the collective effects in terms of configurational mixing. This has been done for the masses 18 and 19 by Elliott and Flowers [34] with very good results. A similar calculation for the mass 16 has recently been performed [35]. The preliminary results indicate a remarkably good agreement with the present experiment. Both the general shape of the cross-section curve and the branching ratios for the protons agree. It would also be of very great interest to compare the experimental angular distributions with the theoretical distributions which one should be able to calculate on the basis of this work. It might be possible to obtain a satisfactory description of the photodisintegration of oxygen with this method.

(γ,α) *reaction*

The result of the present (γ,α) experiment is that in the energy range 10–15 Mev the α-emission mainly goes through two levels at 11.3 and 12.5 Mev. These levels must be assigned the spin 2 and even parity corresponding to electric quadrupole absorption. The reason is that reactions induced by electric dipole and magnetic dipole absorption are forbidden by selection rules. The electric dipole absorption can only go to $T = 1$ states in O^{16}, and the decay must go to $T = 1$ states in C^{12}. Hence this process cannot occur in the energy range investigated in the present work. The $1+$ states excited by magnetic dipole absorption cannot decay to the ground state of C^{12} since there is no change of parity. Since it has been shown that the α-particles correspond to ground state transitions this process is also excluded. This leaves electric quadrupole absorption as the only remaining possibility. The angular distribution of the α-particles support this assignment as has been shown above.

It is interesting to compare the present results with the predictions of the α-particle model. It is well known that this model has had some success when applied to light nuclei of the $A = 4n$ type. Especially in O^{16} there have been attempts to identify levels calculated from the model with the experimentally known levels. Dennison [36] and more recently Kameny [37] have made such calculations. The (γ,α) reaction should offer a good opportunity for testing the α-particle model. A level based on this model corresponds to rotation and vibration of a structure of four α-particles. Since this model implies that the α-particles retain their identity inside the nucleus, at least for a certain time, a level of this type should have a high probability for α-emission. It should be higher than for a level of more complicated structure. The absorption cross-section for the various levels predicted by the α-particle model might well vary considerably, however. The model might, therefore, predict levels which are not seen in the present experiment. One would, however, expect a certain correlation between the calculated and experimental levels. If this is not the case, it would mean a serious difficulty for the α-particle model.

The present experiment covers the energy range from about 10 Mev to about 18 Mev. At the higher energies, above 15 Mev, proton emission starts to compete very strongly. Also the spectrum of the bremsstrahlung used in this experiment falls off rapidly for the higher energies. Hence the levels above 15 Mev are not likely to show up so well in the α-particle spectrum. In the region of interest the α-particle model according to Kameny predicts 2+ levels at 11.21 and 13.07 Mev. These values are to be compared with the experimental values 11.3 and 12.5 Mev. The agreement is rather striking. The deviations are well within the uncertainties of theory and experiment. Hence the present work suggest the conclusion that the α-particle model is applicable for the (γ,α) reaction in O^{16}.

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NOTE ADDED IN PROOF

After the completion of the present work a detailed account of the work of Elliott and Flowers on the odd parity states of O^{16} has appeared (Elliott and Flowers, private communication). The agreement with our experimental work is very good. Some of the most important points will be mentioned here.

The calculations give five $J=1-$, $T=1$ states. The radiation width is small for two of these states. The remaining three with the energy values 17, 23 and 25 Mev have the widths 0.14, 12.0, and 5.8 keV, respectively. Each one of these single particle states will be splitted up in a band of many small resonances due to the mixing with similar states of a more complicated configuration. The shape of the giant resonance should be given by the three single particle states, however. This gives a good agreement with the experimental cross-section curve. The branching ratio for the proton groups to the 6.3 Mev state and the ground state is calculated to 3.03. The experimental value is 3.3.

The experimental angular distributions are also in good agreement with the work of Elliott and Flowers. The single particle states in the giant resonance correspond to a mixture of the configurations $p^{-1}d$ and $p^{-1}s$. The angular distribution should correspond to a mixture of s-wave and d-wave. The coulomb barrier surpresses the d-wave more than the s-wave and the angular distributions should be predominantly isotropic, especially at low proton energies. The 17 Mev state has a very small s-width, however, and the corresponding proton group should have a rather pure d-wave distribution. All this is in agreement with the present experiment.

It should finally be mentioned that the branching ratio to the N^{15} levels above 6.3 Mev according to the theoretical work is small. Hence the observed proton groups going to these levels must correspond to more complicated modes of excitation, in which the energy is shared among two or several nucleons.

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